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*ASP Conference Series, Vol. **VOLUME**, **PUBLICATION YEAR***
EDITORS

Probing the physics of relativistic jets through X-ray observations

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Abstract. The broad band sensitivity and flexibility of the *Beppo*SAX satellite have allowed unprecedented studies of the X-ray emission from blazars. Here we focus on recent results on the SEDs of a group of blazars with emission lines, allowing to estimate both the luminosity in the jet and the luminosity of the accretion disk. Implications for the origin of the power carried by relativistic jets are considered.

1. Introduction

It is now generally accepted that the blazar "phenomenon" (highly polarised and rapidly variable radio/optical continuum) is due to a relativistic jet pointing close to the line of sight (Blandford and Rees, 1978). We further propose that, rather than trying to define a dividing line between objects with or without emission lines (flat spectrum quasars vs. BL Lacs) or between radio bright and X-ray bright BL Lacs, the most productive approach at present is to emphasize the continuity of properties within a single blazar population.

Here and in the following we will assume that Quasars with Flat Radio Spectrum (FSQs, which include OVVs and HPQs) and BL Lac objects are essentially "similar" objects in the sense that the nature of the central engine is similar apart from some basic scales. Our aim is to start from a (common) physical comprehension of the phenomenology with the goal of understanding the role of more fundamental parameters, like the central black hole mass, angular momentum and accretion rate, in determining the properties of the jets and of the associated disks.

2. The Unified Framework for the SEDs of blazars.

It was noted early on that the SEDs of blazars exhibited remarkable systematic properties (Landau et al. 1986, Sambruna et al. 1996). The subsequent discovery by the Compton Gamma Ray Observatory of gamma-ray emission from blazars (a summary can be found in Mukherjee et al. 1997) was a major step forward, showing that in many cases the bulk of the luminosity was emitted in this band and questioning the importance of previous studies of the SEDs at lower frequencies.

A systematic investigation on the SEDs of the main complete samples of blazars (X-ray selected, radio-selected and Quasar-like, Fossati et al. 1998) including gamma-ray data showed that the systematic trends found previously in-

deed persisted, suggesting a continuity of spectral properties (spectral sequence). All the SEDs show two broad components with peaks in the $10^{13}-10^{18}$Hz and $10^{21}-10^{25}$Hz ranges respectively. Both peaks appear to shift to higher frequencies with decreasing luminosity. We will call red and blue the objects at the different extremes of the sequence.

Beamed synchrotron and inverse Compton emission from a single population of relativistic electrons accounts very well for the observed SEDs except in the radio to mm range where effects of selfabsorption and inhomogeneity are important (see also Kubo et al. 1998). We recall that the relativistic particle spectrum must be "curved" in order to explain the peaks observed in the SEDs. The curvature is often modelled with a broken power law. The model predicts that the synchrotron and IC emissions should vary in a correlated fashion, especially at frequencies near the peaks. Despite the difficulty of getting adequate data, this has been verified at least in some well studied objects. In the following we will assume that this emission model holds in general.

Ghisellini et al. 1998 derived the physical parameters of jets of different luminosities along the sequence applying the above model with seed photons of internal (SSC) as well as external (EC) origin. The results suggest that i) the importance of external seed photons increases with increasing jet luminosity ii) the "critical" energy of the radiating electrons decreases with increasing (total) radiation energy density. The latter dependence is physically plausible since the radiation energy density determines the energy losses of relativistic particles. If the critical electron energies were determined by a balance between injection/acceleration and cooling processes the latter dependence could be understood.

This "unified" theoretical scheme, needs to be tested in many respects. One can think of at least two ways of doing so : i) determine the physical parameters in individual objects with improved data ii) understand the mechanisms of particle acceleration and injection from detailed variability studies.

More indirectly, if FSQs and BL Lacs contain "similar" jets (at least close to the nucleus) as suggested by the continuity of the SEDs, we still need to understand the differences in emission line properties. Also in this respect continuity could hold in the sense that the accretion rate may decrease continuously along the sequence but the emission properties of the disk may not simply scale with the accretion rate.

3. Studies of individual objects.

For red blazars the study of the synchrotron component is difficult, because the Synchrotron peak, falls in the poorly covered IR - FIR range. Furthermore the study of the gamma-ray component in the MeV-GeV region of the spectrum has been difficult in the last few years due to the loss of efficiency of EGRET and is now impossible after reentry of CGRO. Thus relatively little progress has been made lately.

We show in Fig. 1 the case of one of the best studied sources, 3C 279, observed with *Beppo*SAX in January 1997 simultaneously with CGRO (Hartman et al. 2000,) and close in time (December 1996) with ISO (Haas et al. 1998). The source was found to be in a rather low state, not far from the low state

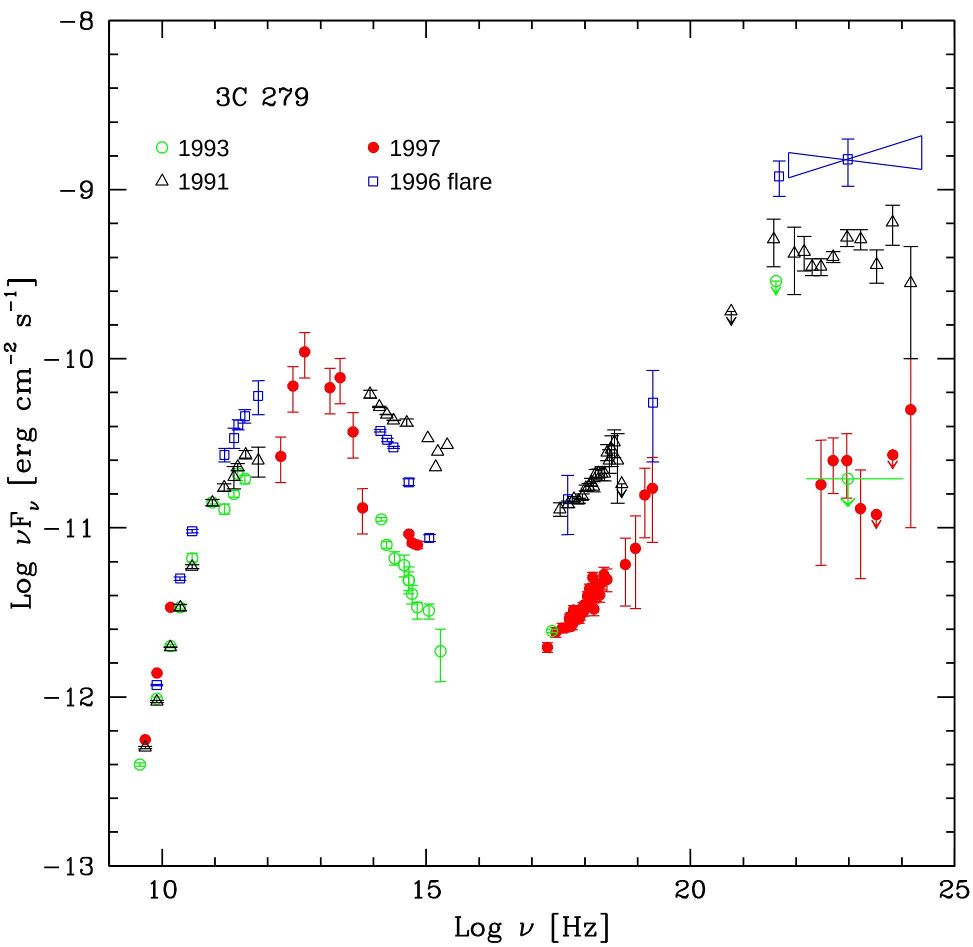

Figure 1. Quasi-simultaneous SEDs of the quasar 3C279 taken in the different epochs. The *Beppo*SAX and EGRET data taken in 1997 are almost exactly contemporaneous, while the ISO spectrum is taken one month before.

observed in 1993 (also shown) (Maraschi et al. in preparation). Also shown for comparison are the two highest states recorded in 1991 and 1996l .

A general correlation of the optical X-ray and γ-ray fluxes is apparent as predicted. The synchrotron peak however, which would help a lot constraining models, is difficult to localize. The ISO data are consistent with those at higher and lower frequencies (Jan 1997) at the two ends of the ISO range but suggest an additional, highly luminous (of order 10^{46} erg s^{-1} thermal component. The origin of such component is not easy to assess.

The situation is better for blue blazars. In several sources of this class the Synchrotron component peaks in the X-ray band, where numerous satellites can provide good data. In few bright extreme BLLac objects the high energy γ-ray component is observable from ground with TeV telescopes (for a general account see Catanese & Weekes 1999). In these particular cases the contemporaneous X-ray/TeV monotoring demonstrated well the correlation between the Synchrotron and the IC components. A very good example is Mkn 421 for which we obtained the observation of a simultaneous TeV/X-ray flare with Whipple and *Beppo*SAX in 1998, probing for the first time the existence of correlation on short (hour) time scales (Maraschi et al. 1999; see also Takahashi et al. 1999, Catanese & Sambruna 2000). When the position of the two peaks can be well determined observationally, as is possible in this type of sources, robust estimates of the physical parameters of the jet can be obtained (e.g. Tavecchio et al. 1998). This was done for both Mkn 421 and Mkn 501 (Maraschi et al. 1999, Pian et al. 1997, Tavecchio et al., submitted).

The broad band response of *Beppo*SAX allows a reliable determination of the position of the synchrotron peak, $E_{\rm peak}$, if it falls between 0.1 and 100 keV. We could verify that during the flare of Mkn 421 mentioned previously $E_{\rm peak}$, moved to higher energies with increasing intensity (Fossati et al. 2000). The same behaviour was exhibited in a more dramatic way by Mkn 501. Its synchrotron peak moved to $E > 100$ keV during the extraordinary activity in April 1997 (Pian et al. 1998). Subsequent snapshot spectra obtained with *Beppo*SAX showed a systematic decrease of $E_{\rm peak}$ down to $\simeq 0.1$ keV in June 1999 while the source was fading. Over this two year period the X-ray light curve as measured by the ASM aboard XTE was not monotonic with an overall decay interrupted by flares. Thus our observations show that $E_{\rm peak}$ correlates with luminosity not only along individual flares but also on much longer timescales.

The $E_{\rm peak}$ vs. luminosity relation observed (higher $E_{\rm peak}$ for higher luminosity) is opposite to that found in the "spectral sequence", where the peak falls at *lower* frequencies for objects of higher luminosity.

One way to reconcile the two types of behaviour is the following. Suppose that the Lorentz factor of particles emitting at the peak $\gamma_{\rm p}$ is determined by a balance between cooling and acceleration processes.

Given that $t_{\rm cool} = {\rm const}/U\gamma$, where U is the total energy density, and using the general expression $t_{\rm acc}(\gamma) = \gamma t_{\rm o,acc}$, found in the theory of diffusive shock acceleration (see e.g. Kirk et al. 1998) one obtains $\gamma_{\rm p} \propto (U t_{\rm o,acc})^{-1/2}$.

This expression is consistent with the correlation found by Ghisellini et al. (1998), $\gamma_{\rm p} \propto U^{-1/2}$ provided that the basic acceleration timescale $t_{\rm o,acc}$ is, on average, similar in all sources. Flares in single sources can be interpreted as due to the temporaneous decrease of $t_{\rm o,acc}$ due to changes in the strength of

the acceleration process. The latter scenario seems to apply quite well to Mkn 501 (Tavecchio et al. 2000, submitted), for which it is possible to reproduce the observed variability with the only change of $\gamma_{\rm p}$.

4. Jet power vs. accretion power

Finally we wish to report on work in progress on luminous blazars with emission lines observed with *Beppo*SAX. These are at the high-luminosity end of the sequence, with the Synchrotron peak in the FIR region. In these sources the X-ray emission is believed to be produced through the IC scattering between soft photons external to the jet (produced and/or scattered by the Broad Line Region) and *electrons at the low energy end of their energy distribution.* Thus measuring the X-ray spectra and adapting a broad band model to their SEDs yields reliable estimates of the total number of relativistic particles involved, which is dominated by those at the lowest energies. This is interesting in view of a determination of the total energy flux along the jet (e.g. Celotti et al. 1997, Sikora et al. 1997). The "kinetic" luminosity of the jet can be written as

$$L_{\rm j} = \pi R^2 \beta c U \Gamma^2 \tag{1}$$

(e.g. Celotti et al. 1997) where R is the jet radius, Γ is the bulk Lorentz factor and U is the total energy density in the jet, including radiation, magnetic field, relativistic particles and eventually protons. If one assumes that there is 1 (cold) proton per relativistic electron the proton contribution is usually dominant.

In high luminosity blazars the UV bump is often directly observed and/or can be estimated from the measurable emission lines, yielding direct information on the accretion process in the hypothesis that the UV emission derives from an accretion disk. Thus the relation between accretion power and jet power can be explored. This approach was started by Celotti et al. (1997) but their estimates of $L_{\rm jet}$ were obtained applying the SSC theory to VLBI radio data which refer to larger scales. Our study involves the analysis of the *Beppo*SAX data, modeling the overall SED and deriving the physical parameters for the jet. For three sources the results have been already published (Tavecchio et al. 2000). For other 6 sources the results used here are preliminary.

As an example of the quality of the data we are using, the SEDs of 2251 +158 and 1641+339 are shown in Fig. 2. The adopted models are also plotted. Note that 1641+339 was *not* detected by EGRET. Nevertheless its medium to hard X-ray spectrum and overall SED indicate that a gamma-ray component similar to other sources is likely to be present.

In addition to the 9 emission line blazars recently observed we included in the analysis 3C 279 and four BL Lac objects for which we had previuos good quality *Beppo*SAX data (namely BL Lac, ON231, Mkn 501 and Mkn 421) (Tagliaferri et al. 2000a, Tagliaferri et al. 2000b, Tavecchio et al. 2000 submitted, Maraschi et al. 1999).

In all cases physical parameters were estimated by means of a homogeneous SSC+EC model and the kinetic luminosity of the jet including protons, $L_{\rm P}$, as well as the total luminosity radiated by the jet in the observer frame ($L_{\rm rad}$) were derived accordingly. The luminosity of the disk could be estimated for all objects except the latter three BL Lac, for which we could set only upper limits

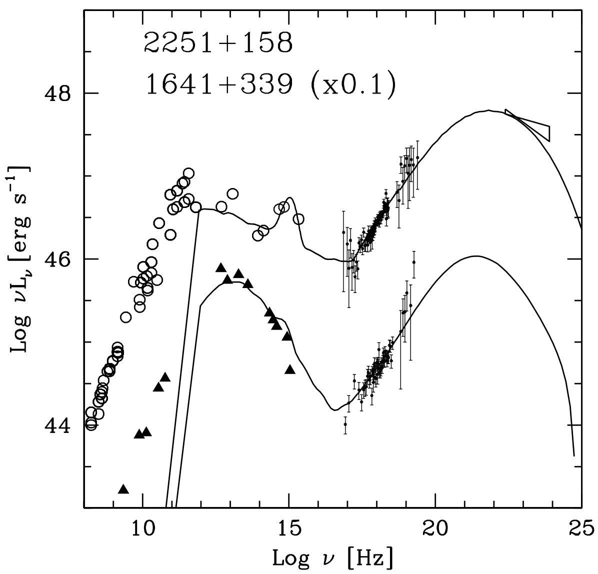

Figure 2. Overall SEDs of two emission-line Blazars, 2251+158 (open circles) and 1641+339 (triangles, for clarity the SEDs has been multiplied by 0.1). Although the 1641+339 was not detected by EGRET the overall SED appears similar to those of the other gamma-ray quasars.

on the luminosity of their putative accretion disks. For 3C 279 and BL Lac, the presence of broad Ly_α and H_α respectively allowed to estimate the ionizing continuum (e.g. Corbett et al. 2000).

The comparison between the total radiative luminosity $L_{\rm rad}$ and the kinetic luminosity of the jet $L_{\rm P}$ is shown in Fig 3a. The ratio between these two quantities gives directly the "radiative efficiency" of the jet, which turns out to be $\eta \simeq 0.1$, though with large scatter. The line traces the result of a least-squares fit: we found a slope ~ 1, indicating a rather constant radiative efficiency along the Blazar sequence (note that the data cover a wide range of about 5 orders of magnitude).

In Fig. 3b we compare the luminosity of the jet, $L_{\rm rad}$, which is a *lower limit* to $L_{\rm jet}$, with the luminosity of the disk, $L_{\rm disk}$.

The first important result is that on average the minimal power transported by the jet is *of the same order* as the luminosity released in the accretion disk. This result poses an important condition for models elaborated to explain the formation of jets.

Two main lines of approach consider either extraction of rotational energy from the black hole itself or magnetohydrodynamic winds associated with the inner regions of accretion disks. Let us parametrize the two possibilities as follows. Blandford & Znajek (1977) summarize the result of their complex analysis in the well known expression:

$$P_{BZ} \simeq B_0^2 r_g^2 a^2 c \tag{2}$$

Assuming maximal rotation for the black hole ($a = 1$), the critical problem is the estimate of the intensity reached by the magnetic field threading the event horizon, which must be provided by the accreting matter. Using a spherical free fall approximation with $B_0^2/8\pi \simeq \rho c^2$ one can write

$$P_{BZ} \simeq g\dot{M}c^2 \tag{3}$$

where $P_{acc} = \dot{M}c^2$ is the accretion power and g is of order 1 in the spherical case but in fact it is a highly uncertain number since it also depends on the field configuration. Several authors have recently discussed this difficult issue: the arguments discussed by Ghosh & Abramovicz (1997) (GA; see also Livio, Ogilvie & Pringle 1999) plus equipartition within an accretion disk described by the Shakura and Sunyaev (1973) model lead to $g \simeq 1$ when gas pressure dominates. Unfortunately at high accretion rates when radiation pressure dominates its growth is limited. Frame dragging by the rotating hole may however increase g to values even larger than 1 (Meier 1999).

As argued strongly by Livio et al. the accretion flow itself may power jets through a hydromagnetic wind. However for consistency only some fraction $f\dot{M}c^2$ can be used to power the jet. Further recall that the luminosities observed from the jet and disk are related to their respective powers by efficiency factors $L_{rad} = \eta P_{jet}$; $L_{disk} = \epsilon P_{acc}$.

Using the condition that $P_{jet} \leq (P_{BZ} + fP_{acc})$ together with the previous relations we finally find

$$L_{rad} \leq \frac{\eta(g+f)}{\epsilon} L_{disk}. \tag{4}$$

One can account for the observed relation between L_{rad} and L_{disk} if for instance $\eta \simeq \epsilon \simeq 0.1$ and f or g or both are close to 1. It is also possible that $\epsilon << 0.1$ if the optically thick emission derives from radii larger than $3r_G$ or if the disk is optically thin as may happen at low accretion rates (Blandford 1990). This may be necessary at low luminosities to explain why disks are not seen (upper limits). However at high luminosities there is an additional condition deriving from the total luminosities observed. At 10^{47} erg s^{-1} the Eddington luminosity implies a mass of 10^9 $M_\odot$ and an accretion rate of 10 $M_\odot$ y^{-1} for $\epsilon = 10^{-1}$. It seems then difficult to invoke lower efficiencies.

For comparison we show in Fig 3b the estimates for the rotational power derived by GA for various values of the mass of the central black hole as a function of the luminosity observed from the disk. The latter is related to the accretion rate which appears in the formulae of GA adopting $\epsilon \simeq 0.1$. Clearly the model fails to explain the large power observed in the jets of bright quasars, even for BH masses ($M \sim 10^9 M_\odot$). This is because in the radiation pressure dominated region of the disk the pressure used to estimate the magnetic field via equipartition does not increase with the accretion rate.

5. Conclusions

The study of broad band SEDs and their variability is essential for understanding blazars. A unified approach is possible and should be tested. While the phenomenological framework is suggested to be "simple" (e.g. "red" blazars are

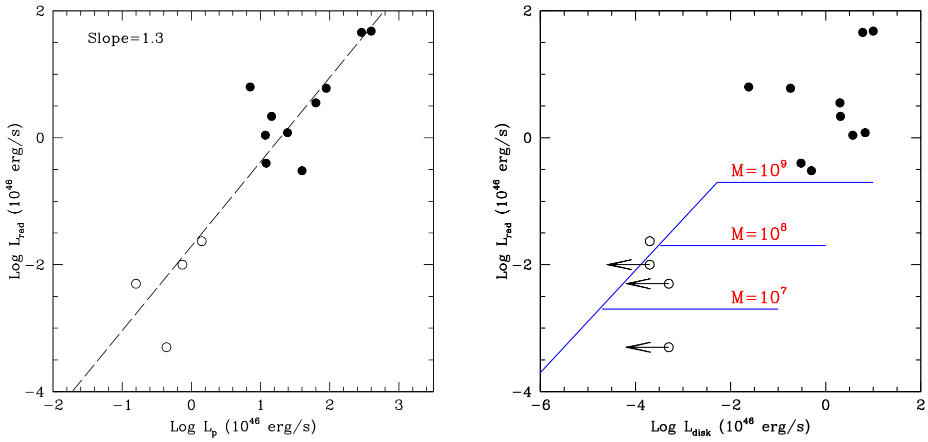

Figure 3. *Left:* Radiative luminosity vs. jet power for the sample of Blazars discussed in the text (open circles represent BL Lac objects). The dashed line indicates the least-squares fit to the data. *Right:* Radiative luminosity of jets vs disk luminosity. The solid lines represent the *maximum* jet power estimated for the Blandford & Znajek model for black holes with different masses (in Solar units).

highly luminous, have low average electron energies and emit GeV gamma-rays while "blue" blazars have low luminosity, high average electron energies and emit TeV gamma-rays) we do not yet know what determines the emission properties of jets of different power nor what determines the jet power in a given AGN. There is however the exciting prospect that such problems can be tackled with data that can be gathered in the near future.

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